

Refining light stop exclusion limits with W^+W^- cross sections

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Abstract

If light supersymmetric top (stop) quarks are produced at the LHC and decay via on- or off-shell W -bosons they can be expected to contribute to a precision W^+W^- cross section measurement. Using the latest results of the CMS experiment, we revisit constraints on the stop quark production and find that this measurement can exclude portions of the parameter space not probed by dedicated searches. In particular we can exclude light top squarks up to 230 GeV along the line separating three- and four-body decays, $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 W^{(*)}b$. We also study the exclusion limits in case when the branching ratio for these decays is reduced and show significant improvement over previously existing limits.

Keywords: natural supersymmetry, stops, LHC

1. Introduction

Searches for stops — the supersymmetric (SUSY) partners of top quarks — have received significant attention from both ATLAS [1–6] and CMS [7–12]. While limits obtained after Run 1 of the LHC at $\sqrt{s} = 8$ TeV can go, depending on the decay modes studied, up to 800 GeV, there are still parts of parameter space where relatively light stops are allowed, see e.g. the summary plots by ATLAS [13] and CMS [14].

The main motivation for light stops is the so-called natural supersymmetry [15] paradigm which demands that the particles must be close in mass to the ordinary top quark. Unfortunately however, this region of parameter space is particularly difficult to explore due to the background of top quark production. In particular if the stop quark decays via a top quark that is almost on-shell ($\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 t^{(*)}$), no exclusion limit is currently present. Another difficult region of the parameters space can be identified at the border between three- and four-body decays with a (nearly) on-shell W boson ($\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 W^{(*)}b$).

Several recent theoretical studies have attempted to fill these holes in the stop parameter space by using precise predictions and measurements of top quark cross section [16] (see however ref. [17] for a discussion of possible problems with this approach), specialized mono-jet searches [18], recasting other SUSY searches [19] or via angular correlations [20]. A complementary idea is that certain corners of the parameter space might be constrained by looking for signals of stoponium production [21].

An alternative approach presented here is based on the observation that light stops decaying into certain final states can contribute to the W^+W^- cross section measurements [22–26]. Until recently the ATLAS and CMS results were displaying a moderate excess over the standard model (SM) prediction [27–29] but this was determined to be the result of neglected higher order corrections [30–32]. In any case, the fact that the observed cross-section was greater than the predicted background meant that any derived constraints on stop production would have been weak. However, the recent CMS measurement [33] based on the full $\sqrt{s} = 8$ TeV dataset, using the next-to-next-to-leading-order (NNLO) cross section prediction, $\sigma^{\text{NNLO}}(pp \rightarrow W^+W^-) = 59.8_{-1.1}^{+1.3}$ pb [30], and event reweighing [32] turned out to be very well aligned with the SM: $\sigma^{\text{exp}} = 60.1 \pm 4.8$ pb. In this Letter, we recast the CMS analysis as a potential way to constrain the production of light stops.

We focus on three widely studied decay modes that are commonly present in SUSY models with light stops and improve the existing constraints. Assuming that only the light stop and the lightest supersymmetric particle (LSP, in our case the lightest neutralino, $\tilde{\chi}_1^0$) have masses of order of the electroweak symmetry breaking (EWSB) scale we have:

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 t, \quad \text{if } m_{\tilde{t}_1} \geq m_t + m_{\tilde{\chi}_1^0}, \quad (1)$$

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 W b, \quad \text{if } m_{\tilde{t}_1} \geq m_W + m_b + m_{\tilde{\chi}_1^0}, \quad (2)$$

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 f f' b, \quad \text{if } m_{\tilde{t}_1} < m_W + m_b + m_{\tilde{\chi}_1^0}. \quad (3)$$

The three- and four-body decays might compete with loop-mediated two-body decay, $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 c$ [34, 35], but the branching ratios (BR) are highly model dependent here [36–39]. Another possibility is given by:

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^\pm b \rightarrow \tilde{\chi}_1^0 W^{(*)} b, \quad (4)$$

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provided $m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1}$. Depending on the parameter point under consideration, in particular the mass differences between stop and electroweakinos and their mixing character, the chargino mediated (4) and one of the direct decays (1), (2) or (3), may be simultaneously present, see e.g. [40]. This feature would have a significant impact on the expected exclusion limits.

2. Simulation

Monte-Carlo stop samples with up to one additional jet were simulated using **MadGraph5_aMC@NLO** [41] and matched to the **Pythia 6** [42] parton shower. The cross sections were normalized to the next-to-leading-order (NLO) prediction using **NLLfast** [43, 44].

The analysis of the simulated samples was performed using **CheckMATE** [45, 46] and a dedicated implementation of the CMS W^+W^- cross-section measurement. **CheckMATE** uses a specially tuned version of the **Delphes 3** detector simulation [47] and jets were clustered using **FastJet** [48] with the anti- k_T algorithm [49]. The analysis is performed for di-lepton final states with missing energy which for the signal process originates from neutrinos. In order to suppress a dominant SM background, $t\bar{t}$ production, events with b -jets and multiple final-state jets are vetoed. To better understand the $t\bar{t}$ background, CMS defines two signal regions (SR): 0-jet SR without jets with $p_T > 30$ GeV; 1-jet SR with exactly one jet with $p_T > 30$ GeV. These are further subdivided based on whether the final state leptons have different ($e\mu$) or same flavour (ee or $\mu\mu$). The expected and observed event numbers agree well within errors for all SR and therefore the analysis can serve as a constraint for models that contribute to the similar final state.

Our implementation was validated using the event numbers provided by the CMS collaboration for W^+W^- signal and $t\bar{t}$ background [33]. The samples used for validation were obtained using **MadGraph5_aMC@NLO** [41] and hadronised using **Herwig++ 2.7** [50, 51]. The parton distribution function (PDF) sets used were CTEQ6L [52] for leading order generation and CT10 [53] for NLO.

In order to apply limits to stop production we implement two different procedures. For the first we calculate the model independent confidence limits in a modified frequentist approach (CLs method [54]) at 95% for the two flavour inclusive SRs. We then define the stop model as excluded when it predicts a cross section in excess of any of these limits. The second method produces a more stringent model dependent CLs limit at 95% by performing a combined fit to the four separate signal regions. We use **HistFitter** [55] as an interface to **HistFactory** [56], **RooStats** [57], **RooFit** [58] and **ROOT** [59, 60], to allow all background sources to float independently whilst including the correct correlated systematics.

Many of the backgrounds to W^+W^- production are determined with a data driven technique in the CMS anal-

ysis. Essentially control regions are defined for the various backgrounds that are only expected to contain a small contribution from the W^+W^- process under study. These are used to normalise the various backgrounds and Monte-Carlo is then used to extrapolate to the W^+W^- signal regions. One may therefore worry that stop production contributes in these control regions, spoiling the normalisation constants.

Unfortunately CMS does not publish the control regions used so it is impossible for us to explore these effects. However, we note that it is possible that stop production contributes to the control region and thus increases the value of the normalisation constant. In turn this could increase the background prediction in the W^+W^- signal regions. Such an effect would actually strengthen the limit we derive on stop production and one may worry about setting a spurious exclusion but we believe that such a possibility does not exist in our study. Firstly, the predicted and measured W^+W^- cross section are now in very good agreement suggesting that any signal contamination can only be slight. Secondly, of most concern for this analysis is the $t\bar{t}$ control region. However, in the parameter region of most interest for our study, $m_{\tilde{t}} \approx m_b + m_W + m_{\tilde{\chi}^0}$, this corresponds to the b -quarks being extremely soft. Hence it is very unlikely, that this final state will contribute to a $t\bar{t}$ measurement at all.

3. Results

The obtained exclusion limits for stop decaying via (1), (2) or (3) with 100% branching ratio are shown in Fig. 1. The best exclusion limit is obtained along the line $m_{\tilde{t}_1} \simeq m_W + m_b + m_{\tilde{\chi}_1^0}$ and is exactly where no current LHC search sets a limit on these models. The W^+W^- measurement allows us to constrain stop masses up to ~ 220 GeV for a LSP mass of ~ 130 GeV. We also note the additional exclusion for stop masses ~ 170 – 190 GeV for decay mode (2) where an intermediate top quark is nearly on-shell that also extends the limits from dedicated stop searches.

The reason that the W^+W^- cross section measurement is so sensitive along this line is that the final states are most similar to the actual SM production of W^+W^- pairs: the W boson is (nearly) on-shell and the b -jet is rather soft, significantly reducing b -jet veto effectiveness. On the other hand, this region is problematic for dedicated stop searches due to its similarity to the SM background. Dedicated stop searches attempt to place cuts that act as a discriminator between signal and background. However in regions where the signal has very similar features to the background this approach breaks down and consequently our approach is complementary to other searches.

It was shown in Ref. [39] that the branching ratio for decays (2) and (3) can be substantially reduced in favour of loop-mediated flavour-changing two-body decay, $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 c$. Such a reduction can pose a significant challenge for dedicated stop searches as can be seen for example in

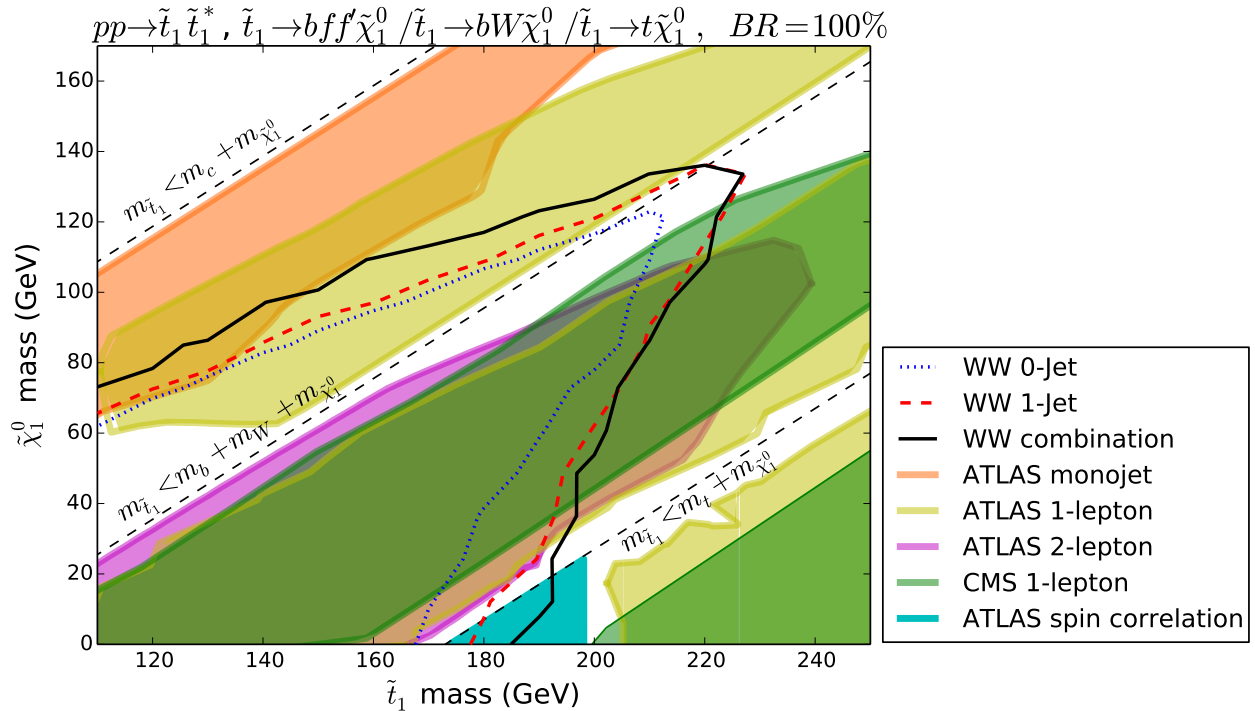


Figure 1: The exclusion limits for stop pair-production in $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane assuming that only decay modes (1)-(3) are allowed, respectively. The dotted-blue line denotes the exclusion using 0-jet signal region and the red-dashed 1-jet signal region of Ref. [33]. The black solid-line is for the combined exclusion, as discussed in Sec. 2. The experimental exclusions were extracted from the following studies: ATLAS monojet [5], ATLAS 1-lepton [2], ATLAS 2-lepton [4], CMS 1-lepton [9], ATLAS spin correlation [6].

Fig. 12 of Ref. [9]. Therefore, we compare exclusion limits obtained in the current study with the results reported by collaborations, but now assume $BR(\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 W^{(*)} b) = 0.6$.

In Fig. 2 we see that the limits are severely weakened and much more of the stop parameter space is unconstrained.¹ The W^+W^- measurement is still effective however and allows us to constrain stop masses up to ~ 180 GeV for a LSP mass of ~ 80 GeV. In fact for low stop masses we can successfully exclude models with $m_{\tilde{\chi}_1^0} < 60$ GeV which current searches are not sensitive to.

4. Summary

We analysed constraints on the stop sector in light of the recent measurement of W^+W^- production cross section by CMS. We show that this measurement provides constraints on light top squarks that are complementary to the dedicated LHC searches.

The best sensitivity is obtained along the line where an intermediate decay-mediating W boson becomes on-shell, where the conventional stop searches have a particular weakness. Assuming that this is the only available decay mode, the reach is $m_{\tilde{t}_1} \gtrsim 230$ GeV. The method retains its sensitivity even for significantly reduced branching ratios to the analysed final state. We demonstrate that in

case of $BR = 0.6$, stops with masses $m_{\tilde{t}_1} \lesssim 180$ GeV are also excluded. We note that in the reduced branching fraction scenario, the other searches are significantly limited and this additionally shows the complementarity of these approaches.

Note added

After completing this study, a summary of ATLAS Run-1 stop searches has been published [61]. It includes a dedicated stop search along similar lines to the suggestion in this Letter. We note that our results for 0-jet SR are consistent with those presented in ref. [61]. However, in some parts of the parameter space, in particular for $m_{\tilde{t}_1} \simeq m_t, m_{\tilde{\chi}_1^0} \simeq 0$, the CMS 1-jet SR [33] offers a stronger bound.

Acknowledgements

KR has been supported by the MINECO (Spain) under contract FPA2013-44773-P; Consolider-Ingenio CPAN CSD2007-00042; the Spanish MINECO Centro de excelencia Severo Ochoa Program under grant SEV-2012-0249; and by JAE-Doc program.

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¹The current available data for the ATLAS monojet study [5] do not allow for a reliable combination when branching ratios of less than 100% exist in a model. In addition, since the study relies on charm tagging that is difficult to reliably simulate with a fast detector simulation we remove the study from this figure.

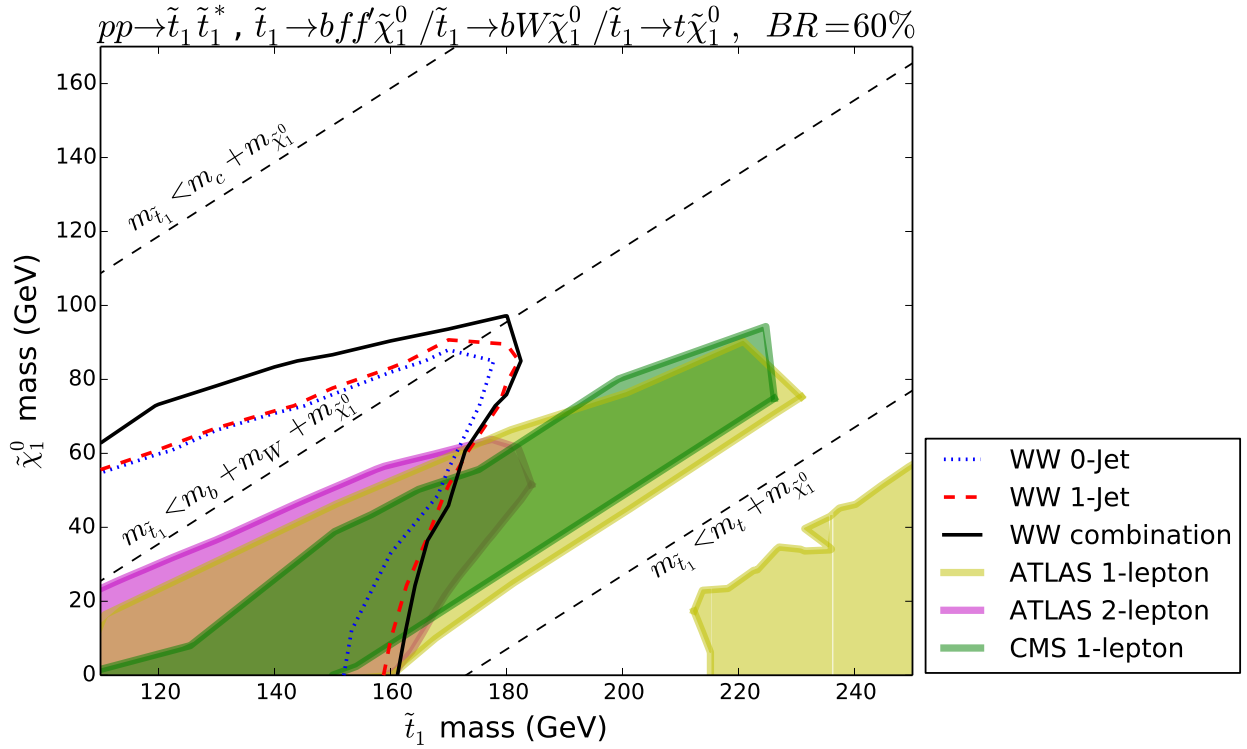


Figure 2: The exclusion limits for stop pair-production in $m_{\tilde{t}_1}-m_{\tilde{\chi}_1^0}$ plane assuming that the branching ratio for decay modes (1)-(3) is 60%. The dotted-blue line denotes the exclusion using 0-jet signal region and the red-dashed 1-jet signal region of Ref. [33]. The black solid-line is for the combined exclusion, as discussed in Sec. 2. The experimental exclusions were extracted from the following studies: ATLAS monojet [5], ATLAS 1-lepton [2], ATLAS 2-lepton [4], CMS 1-lepton [9], ATLAS spin correlation [6].

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